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ABSTRACT

We performed numerical modeling studies to investigate water seepage into underground openings excavated in unsaturated fractured rock. Water seepage is a key factor affecting the performance of a nuclear waste repository such as the one proposed at Yucca Mountain, Nevada. The amount of water dripping into an underground opening depends on the connectivity and permeability of the fracture network as well as on the capillarity of individual fractures intersecting the opening. We developed a high-resolution numerical model of an unsaturated fracture network and examined the appropriateness of seepage predictions using a fracture-continuum model. Model calibrations to liquid-release tests performed at Yucca Mountain are also discussed.

INTRODUCTION

Water seepage into mined openings is of considerable importance for the performance of the proposed high-level nuclear waste repository at Yucca Mountain, Nevada, which would be located in a thick unsaturated zone consisting of fractured ash-flow tuff. Corrosion of the containment system and mobilization of radionuclides strongly depend on the rate and distribution of water seepage into waste-emplacement drifts. To study drift seepage, we performed a series of air-permeability and liquid-release tests in boreholes drilled above short niches excavated into the wall of a tunnel (Wang et al., 1999). In preparation for a detailed analysis of these tests, we performed a numerical study to examine the appropriateness of using a fracture-continuum concept for seepage predictions.

A short discussion of the capillary barrier effect, which is a key mechanism affecting drift seepage rates, is given first, before we discuss modeling results of water percolation and seepage into underground openings using both a discrete feature model and a fracture-continuum model. Finally, we analyze liquid-release test data using inverse modeling techniques.

CAPILLARY BARRIER EFFECT

Under unsaturated conditions, seepage into a cavity is expected to be less than the downward percolation rate because the cavity acts as a capillary barrier. If percolating water encounters the cavity, the relatively strong capillary forces in the formation retain the water, preventing it from seeping into the opening. Water accumulates in the formation at the drift ceiling, where the increase in saturation leads to capillary pressures that are locally less negative than in the surrounding rock, allowing water to be diverted around the drift. If the lateral hydraulic conductivity is insufficient to divert the water, fully saturated conditions are reached locally, and seepage occurs as the capillary barrier fails. The seepage threshold, defined as the critical percolation flux at which dripping occurs, and the seepage rate are thus strongly affected by the capillary pressure and unsaturated hydraulic-conductivity functions as well as the drift geometry. For a given percolation flux, drift seepage is low in formations with strong capillary forces and high conductivity, the latter enabling lateral flow diversion at lower saturations. While increasing both capillarity and permeability reduces seepage, these two parameters are usually negatively correlated, i.e., formations with larger pores or wider fracture apertures show high permeabilities but relatively weak capillary pressures. This negative correlation reduces the probability of very high seepage rates, which would be obtained only in formations that are of low permeability and at the same time show weak capillarity—an unlikely parameter combination.

Analytical solutions to the so-called seepage exclusion problem were developed by Philip (1990) for a variety of drift shapes, assuming steady, uniform downward flow in homogeneous, isotropic porous media, with an exponential relationship between hydraulic conductivity and water potential. Several numerical studies were performed, investigating various aspects of capillary-barrier performance in engineered or natural layered systems (Oldenburg and Pruess, 1993; Ho and Webb, 1999). However, the seepage-exclusion problem has not been analyzed for fractured systems.

The physical processes governing seepage in porous media are also key factors in fractured formations. The effectiveness of the capillary barrier is determined by the capability of individual fractures to hold water by capillary forces and by the permeability and connectivity of the fracture network, which allows water to be diverted around the drift. However, the discreteness of the fractured system increases the importance of the geometric and hydraulic properties in the immediate vicinity of the drift wall, specifically within the layer of increased saturation above the opening. In essence, lateral flow diversion occurs only if the capillary rise in the fracture is larger than the distance from the drift wall to the first fracture intersection, i.e., the average length of the fracture segments intersecting the drift must be short compared to the capillary pressure head. The parameter values estimated by inverse modeling using data from a seepage experiment automatically reflect these conditions, i.e., they are both seepage-relevant and model-related.

DISCRETE AND CONTINUUM MODELS

We simulated unsaturated flow using a discrete feature model (DFM) and demonstrated that reasonable predictions of drift seepage can be made using a simplified fracture continuum model (FCM) (Finsterle, 1999a). The purpose of the DFM was to study discrete flow and seepage behavior, and to generate synthetic characterization data for the subsequent calibration of the FCM. The DFM is a high-resolution, two-dimensional, cross-sectional model of a drift excavated from a fractured-porous formation. The dimensions of the model domain was 6 $\times$ 7 m in horizontal and vertical directions, respectively, and was discretized into regular, square gridblocks with a side length of 0.05 m. In order to create a complex network of discrete, heterogeneous fractures, four permeability fields with different fracture orientations and strongly anisotropic correlation structures were generated using sequential indicator simulations (Deutsch and Journel, 1992) and mapped onto the computational grid. The individual fracture sets were produced by drawing log-permeability values from cumulative distribution functions that yield a high probability for very low values (representing the matrix), a low probability for intermediate values, and a relatively high probability for very high values (representing the fractures). Figure 1 shows the resulting network of heterogeneous fractures with variable orientation, length, and permeability.

On the scale of an individual gridblock, we assume that unsaturated flow can be described using Richards' equation as implemented in the integral finite-difference simulator TOUGH2 (Pruess, 1991). The applicability of continuous relative permeability and capillary pressure functions seems appropriate also for small fracture segments, which are likely to be rough and/or partially filled with porous material. The capillary strength parameter $1/\alpha$ appearing in the van Genuchten (1980) model is assumed to be inversely proportional to the square-root of permeability.

Air-injection tests were simulated to obtain estimates of effective permeabilities for the continuum model. Next, in a sequence of three simulated liquid-release tests, water was injected from a borehole centered above the drift. A certain fraction of the injected water is stored in the formation and diverted around the opening (see Figure 2); the rest drips into the drift, where it is captured and measured. The ratio of the total amount of water that seeped into the opening divided by the released volume is termed "seepage percentage." The seepage percentages of three simulated liquid-release tests were 58, 89, and 89%, respectively. The significant increase in seepage percentage for the second test is a result of a transient memory effect. Water from the first test is used mainly to fill up dead-end fractures and to saturate the matrix; the seepage rate is correspondingly low. For the second test, a much smaller volume is available for storage in the matrix and dead-end fractures, thereby increasing the amount of water flowing in the fractures. As a result, dripping is initiated much earlier, yielding higher seepage percentages. The liquid-release tests lead to both partial flow diversion around the drift and a saturation build-up at the crown, which eventually breaks the capillary barrier. The cumulative amount of water seeping into the opening is recorded as a function of time, separately for each test. The resulting curve of cumulative seepage will be used as the synthetic data for subsequent calibration of the FCM (see Figure 3 below).

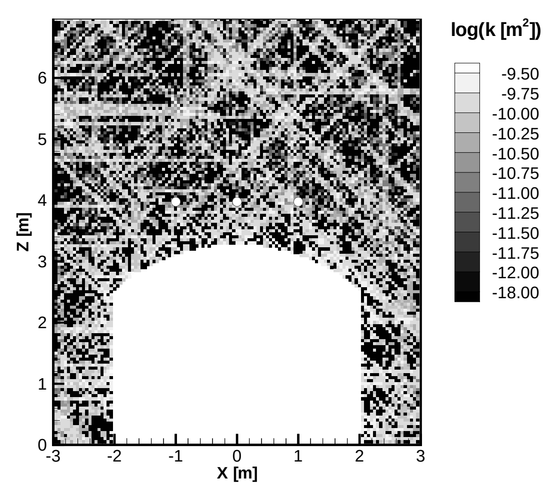

Figure 1. Permeability field of the Discrete Feature Model.

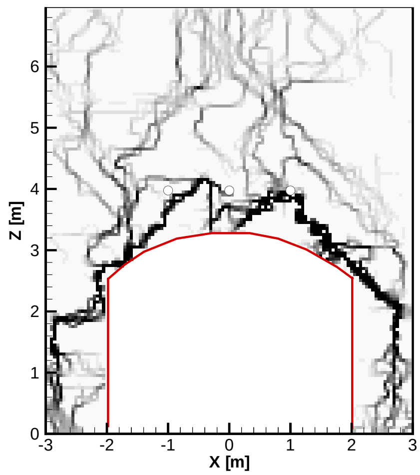

Figure 2. Simulated flow field at the end of a liquid-release test, showing channeling in the fracture network and partial flow diversion around the opening as a result of the capillary barrier effect.

We now discuss the development and calibration of the FCM. While heterogeneous, the FCM lacks the discrete features, the high resolution, and the low-permeability matrix of the DFM. The FCM, which is an abstracted, highly simplified continuum representation of the fractured-porous system, can only be successful in predicting seepage if effective parameters are estimated based on data that reveal seepage-relevant processes. Liquid-release tests are expected to provide this information. The FCM is calibrated against the cumulative-seepage data that were generated with the DFM by adjusting the porosity ϕ and the reference capillary strength parameter $1/\alpha$, which appears in the retention function of van Genuchten (1980). The inversions were performed with the automatic parameter estimation code iTOUGH2 (Finsterle, 1999b).

Figure 3 shows the match obtained. The cumulative seepage data are represented by symbols, where calibration occurs only against the late-time data, shown as squares. Early-time data are not expected to be matched because they are highly governed by the specific geometrical and hydrologic properties of a few fractures that are not represented in a continuum model. Moreover, only the late-time behavior is of interest for subsequent steady-state seepage predictions. The cumulative seepage predicted with the FCM and an initial parameter guess of $\log_{10}(1/\alpha) = 3.0$ and $\log_{10}(\phi) = -2.0$ is shown as a dashed line. The best-fit parameter set was determined to be $\log_{10}(1/\alpha) = 1.60$ and $\log_{10}(\phi) = -2.24$; the corresponding cumulative seepage prediction, which matches the late-time data reasonably well, is shown as a solid line. The flow field after the third liquid-release test as calculated with the FCM and the best-estimate parameter set is visualized in Figure 4, which can be compared to Figure 2. While the details of the flow pattern are different from that of the DFM, the FCM clearly shows a saturation build-up above the crown, leading to a qualitatively similar capillary barrier effect. It can be shown that the calibrated FCM is capable of predicting seepage for a wide range of natural and experimental flow conditions (Finsterle, 1999a).

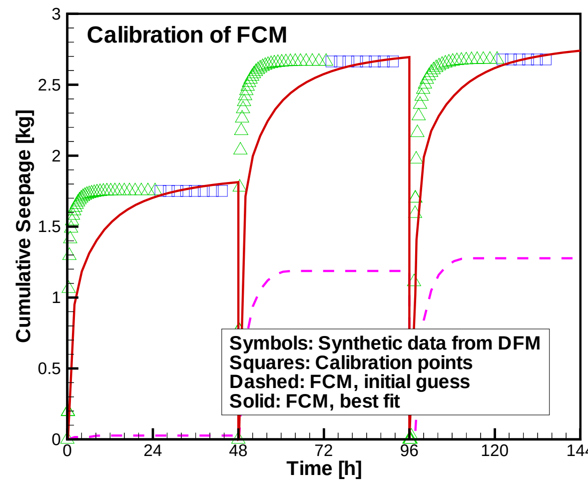

Figure 3. Calibration of the continuum model against late-time cumulative-seepage data from three liquid-release tests simulated with a discrete feature model.

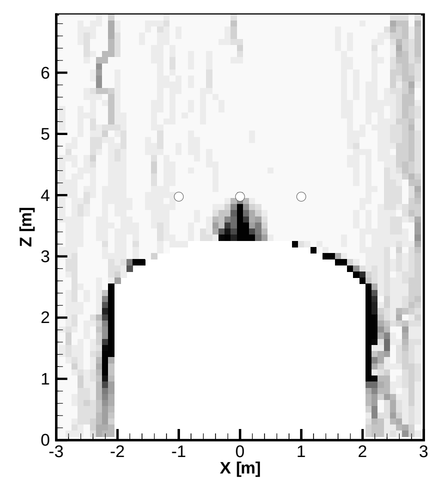

Figure 4. Flow field at the end of the third liquid-release test, predicted by the calibrated fracture-continuum model.

INVERSION OF SEEPAGE DATA

A series of liquid-release tests was performed in a niche excavated as a short opening from a main drift, the Exploratory Studies Facility at Yucca Mountain, Nevada. The tests were performed by sealing a short section of a horizontal borehole above the niche using an inflatable packer system and then releasing water at a constant rate into the isolated test interval. Any water that migrated from the borehole to the niche ceiling and dripped into the opening was captured and weighed to calculate the seepage percentage as defined above. Details about the liquid-release tests can be found in Wang et al. (1999).

A three-dimensional, heterogeneous seepage model was developed. The permeability field was generated using geostatistical methods based on air-permeability data obtained at the site. The computational grid and the $\log_{10}$-permeability distribution are shown in Figure 5. A constant percolation flux of 3 mm/year was applied at the top, a rate significantly lower compared to the amount of water injected during the liquid-release tests. A free-drainage boundary condition was specified at the bottom of the model. The niche itself was at a reference pressure of 1 bar without a capillary suction, i.e., it was assumed that the air directly at the niche wall is at 100% relative humidity. Water was allowed to enter, but prevented from exiting the niche. Thus, the temporal change of water in the niche element represents the cumulative seepage collected in the capture system. No-flow boundary conditions were specified at the left, right, back, and front sides of the model. The model was run to steady state to obtain the initial water-saturation distribution, before injection began.

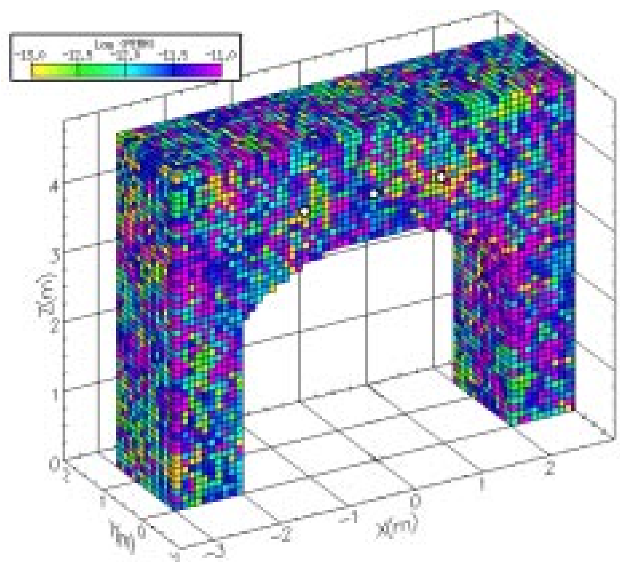

Figure 5. Three-dimensional, heterogeneous seepage model.

Five liquid-release tests described in Wang et al. (1999) were selected for calibration of the seepage model. The five tests were conducted at various injection rates with different lengths of inactivity between individual test events. The seepage percentages observed at the end of each test are thus expected to reveal a number of seepage-relevant processes, including storage effects and the approach of a seepage threshold, i.e., a rate below which no seepage into the drift occurs. In a transient seepage experiment with only a small volume released, the amount of water seeping into the niche mainly depends on the following three factors:

1. The ability of the formation to hold the water by capillary forces, here expressed through an effective van Genuchten parameter $1/\alpha$;
2. The ability of the formation to store the finite amount of water released, here expressed through an effective porosity ϕ, which may include effects of matrix imbibition; and
3. The ability of the formation to divert water around the opening, here expressed through an effective permeability k.

The simulated seepage percentage can be increased by decreasing either capillary strength $1/\alpha$, porosity ϕ, or permeability k. Consequently, all parameter pairs are negatively correlated when inversely determined from seepage data. If only seepage-percentage data are available for calibration, the parameter correlations are expected to be strong, i.e., it is unlikely that they can be determined independently from one another and with a reasonably low estimation uncertainty. We thus chose to determine the porosity ϕ and the reference van Genuchten parameter $1/\alpha$ while fixing permeability k at the value estimated from the air-injection tests. A joint inversion of all five tests yields a very good match. As shown in Table 1, the average differences between the calculated and measured seepage percentages results in prediction standard deviations that are smaller than 0.5% (last column of Table 1). The uncertainties of both the estimated parameters and the predicted seepage percentages were calculated using linear error analysis (Finsterle, 1999b).

The values and uncertainties of the estimated parameters are summarized in Table 2. The estimated capillary strength parameter is relatively low. This results from the fractures not being modeled as discrete features but as a continuum. Discrete fractures intersecting the niche promote seepage; the absence of discrete fractures in the model is partly compensated by a reduction of the estimated $1/\alpha$ value, which has the effect of weakening the capillary barrier and thus increasing seepage. The porosity estimated by inverse modeling seems reasonable, for it includes all fractures involved in the seepage process, including microfractures and the pore space affected by matrix imbibition.

The calibrated model was subsequently used to make predictions of observed seepage percentages from liquid-release tests in other borehole intervals. The good agreement between observed and calculated seepage percentages gives us confidence in the model.

Table 1. Comparison between Measured and Calculated Seepage Percentages and Prediction Uncertainty

Test	Measured	Calculated	Uncertainty
1	22.6	22.7	0.4
2	23.2	23.5	0.4
3	56.2	55.7	0.4
4	4.6	4.6	0.3
5	0.0	0.0	0.1

Table 2. Parameter Estimates and Uncertainty

Parameter	Estimate	Uncertainty
$\log_{10}(1/\alpha\,[\mathrm{Pa}])$	1.82	0.01
$\log_{10}(\phi)$	-2.89	0.01

CONCLUSIONS

We have demonstrated that simulation of seepage into underground openings excavated from a highly fractured formation can be performed using a fracture-continuum model, provided that the model is calibrated against seepage-relevant data such as data from a liquid-release test. The calibration process yields effective parameters that partly account for the discreteness of the fracture network.

The modeling and calibration approach has been successfully applied to seepage data from liquid-release tests performed in a niche excavated at Yucca Mountain. The calibrated model can now be used to predict seepage threshold and seepage percentages for different percolation fluxes, providing crucial information to assess the performance of the potential nuclear waste repository at Yucca Mountain.

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